Light-trapping in polymer solar cells by processing with nanostructured Diatomaceous Earth

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Outline

- **Introduction**
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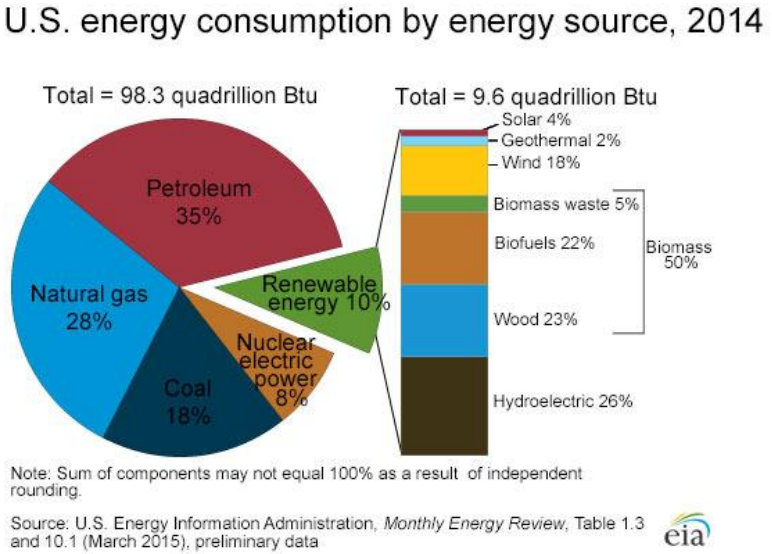
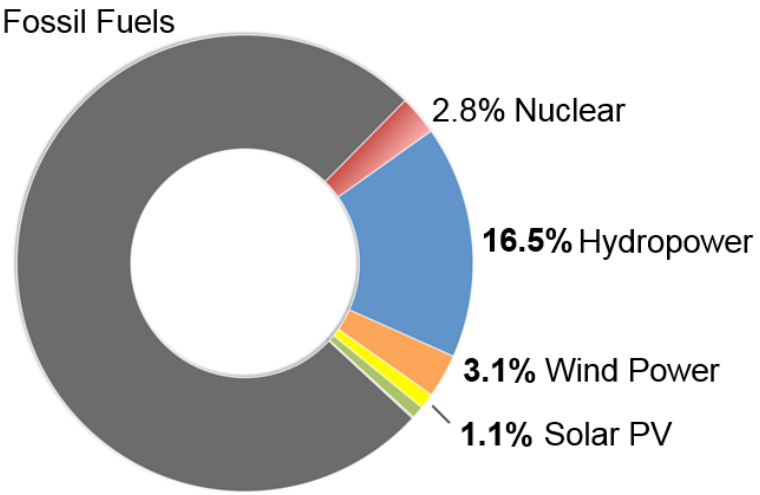
  - Solar Cells
- **Losses in Solar Cells**
- **Solutions to Cell Losses**
  - Biomimetic Approach
  - Experimental Results
  - Simulation Results
- **Future Directions**
  - Design Rules
- **Conclusions**

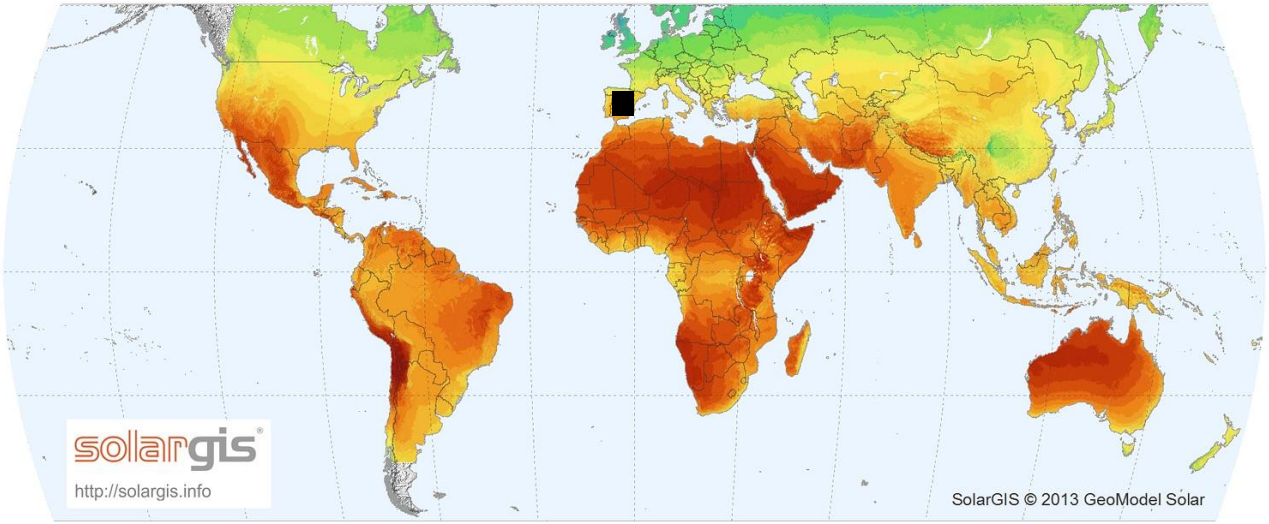
Alternative Energy





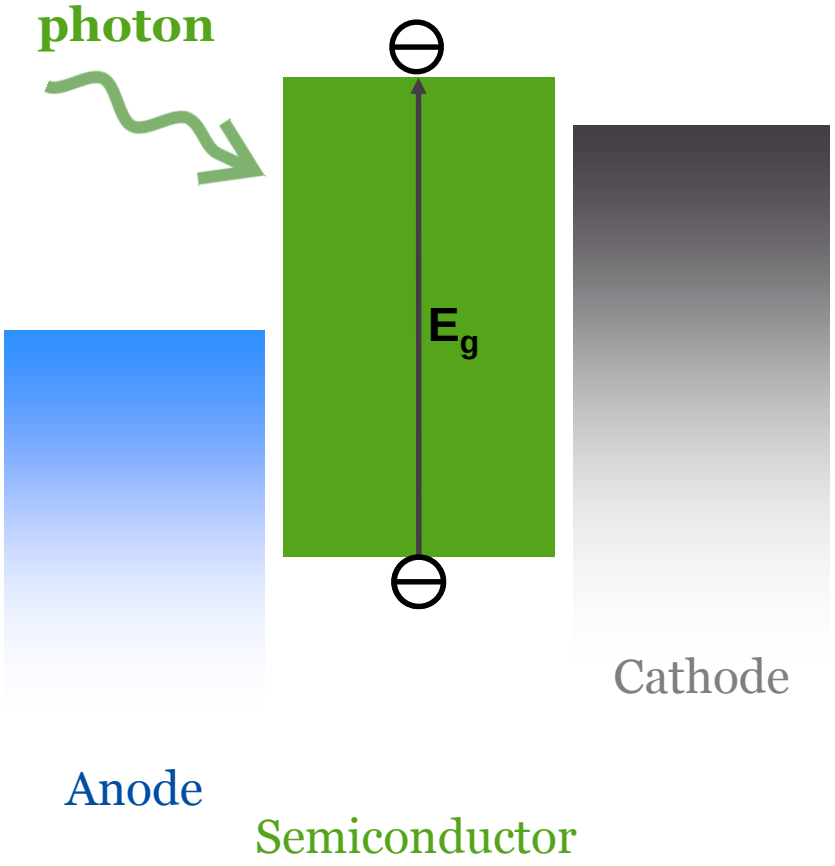
REN21
Renewables 2013. Global Status Report

Why solar?



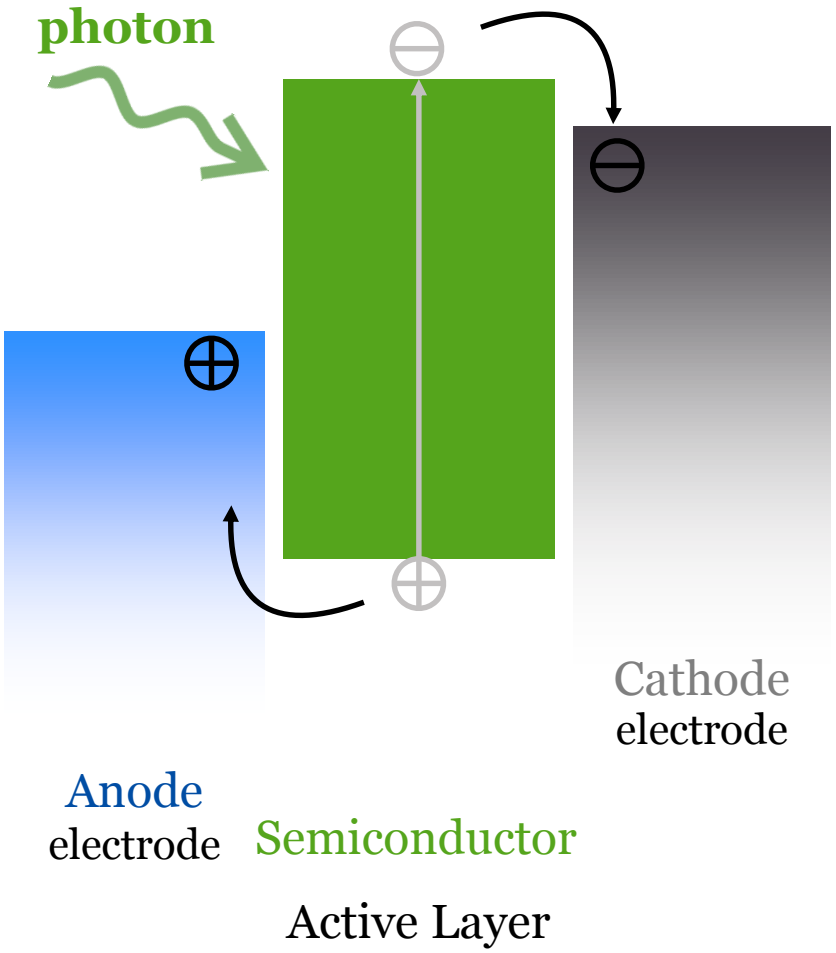
- Sunlight is the most abundant source of renewable energy
- Solar field the area of Spain can fulfill global energy needs
- During operation
  - No pollution
  - No emission
  - No noise

The Solar Cell

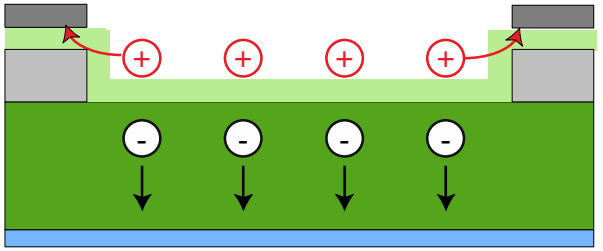


- Converts sunlight directly to electricity
- Photon absorbed by semiconductor
- The electron is excited to the conduction band
- Creation of electron-hole pair

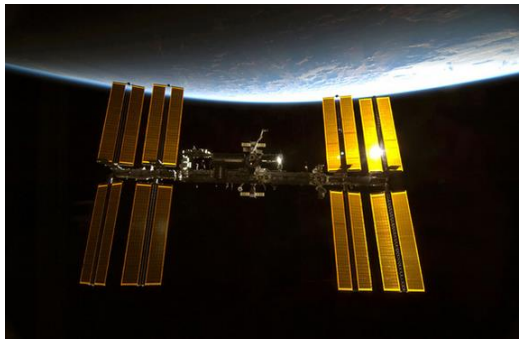
The Solar Cell



- Converts sunlight directly to electricity
- Photon absorbed by semiconductor
- The electron is excited to the conduction band
- Creation of electron-hole pair
- Collection of electrons in cathode
- Collection of holes in anode

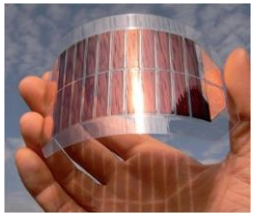


Classes & Applications of Solar



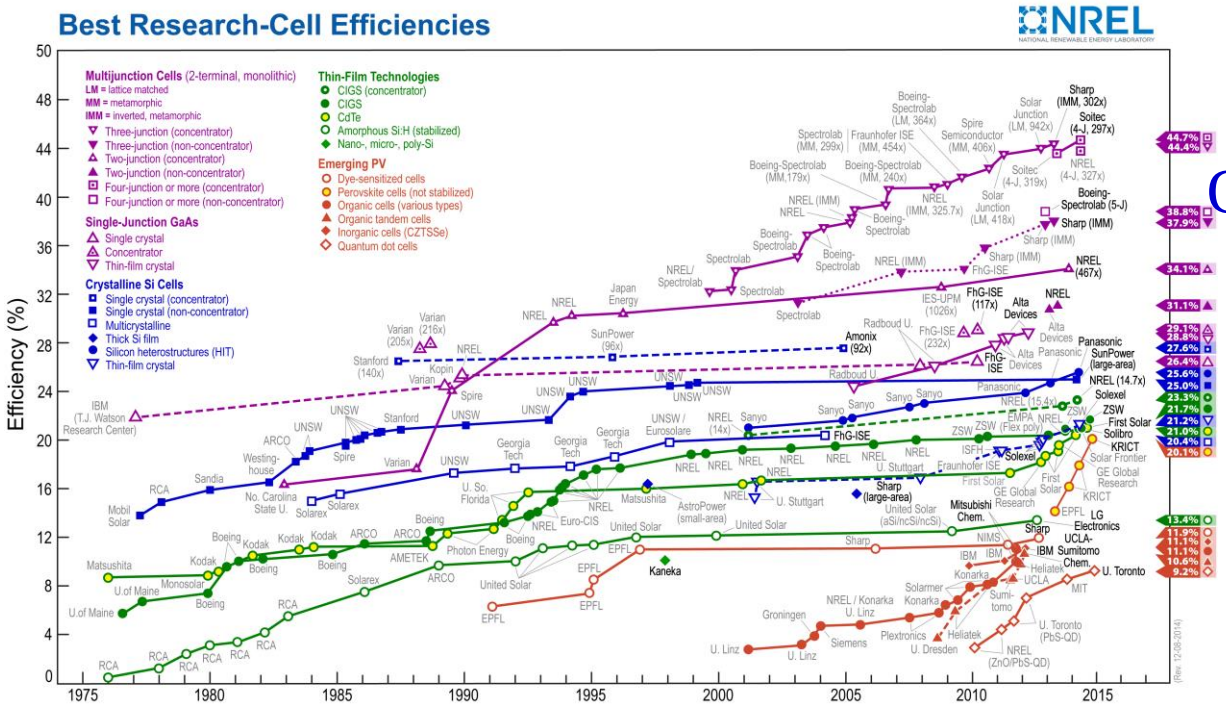
Applications

- Space Exploration
- Defense & Military
- Residential Energy
- Emergency power
- Portable power supplies
- Educational
- Recreational

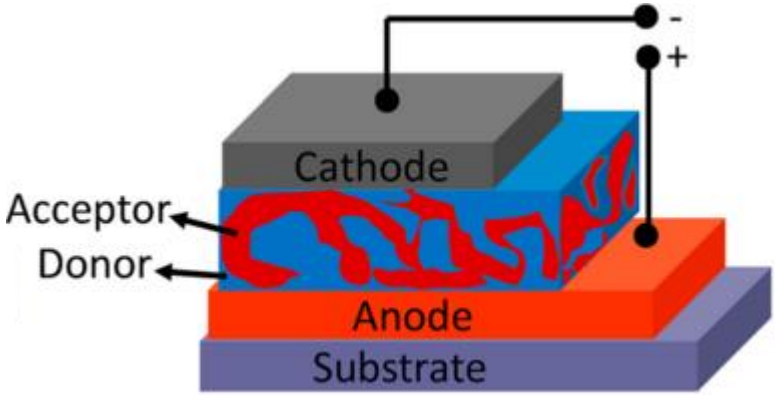


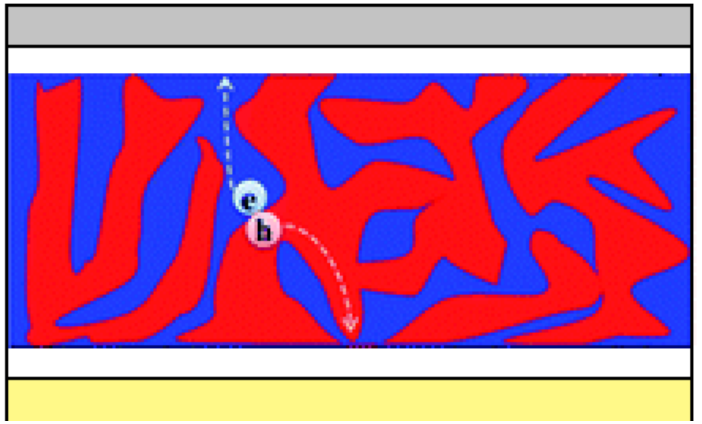
Options

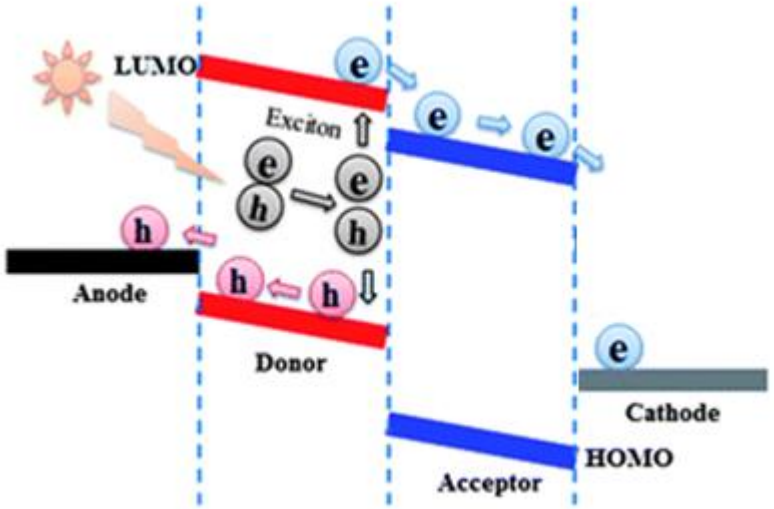
- Organic vs. Inorganic
- Single vs. Multi-Junction
- Crystalline vs. Amorphous
- Flexible vs. Inflexible
- Thin Film
- Hybrid

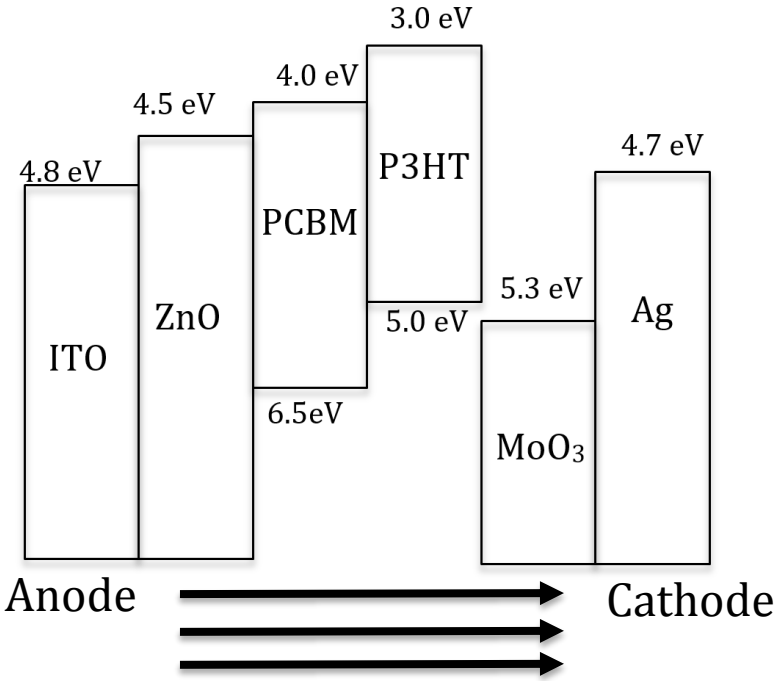


Bulk Heterojunction Solar Cells



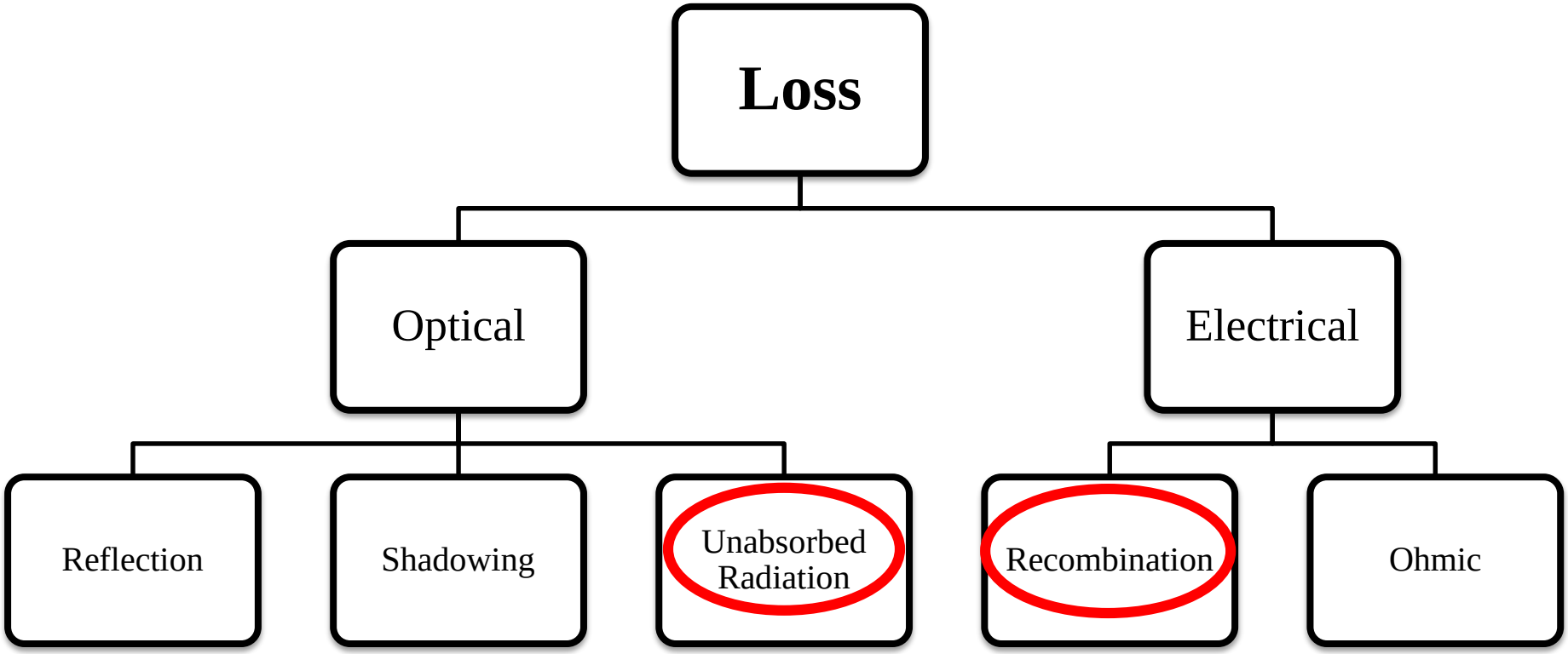


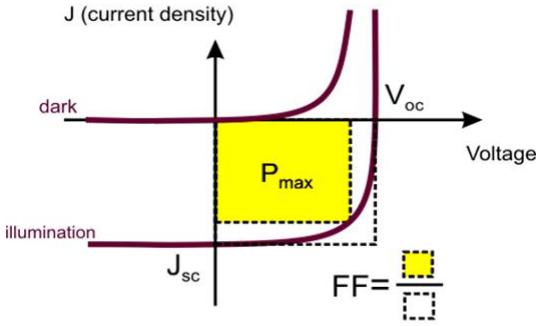




M. He et al. J. Mater. Chem., 2012, **22**, 24253-24264

Losses in Solar Cells

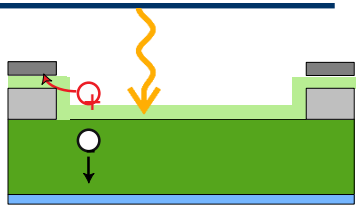


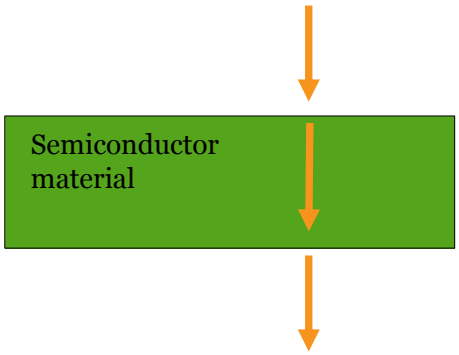


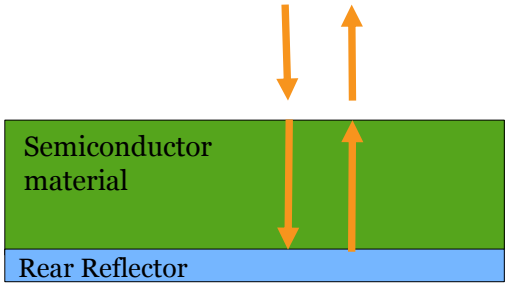
$$\eta_P = \frac{P_{\max}}{P_{in}} = \frac{J_{SC} \times V_{OC} \times FF}{P_{inc}}$$

Light Trapping

- Proposed as early as 1965
- Increase optical path length

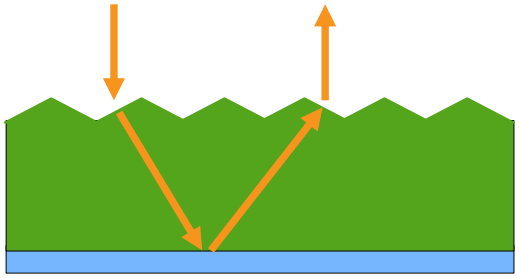


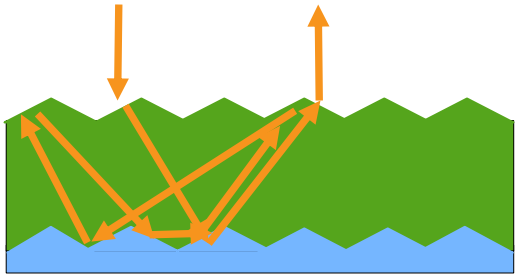




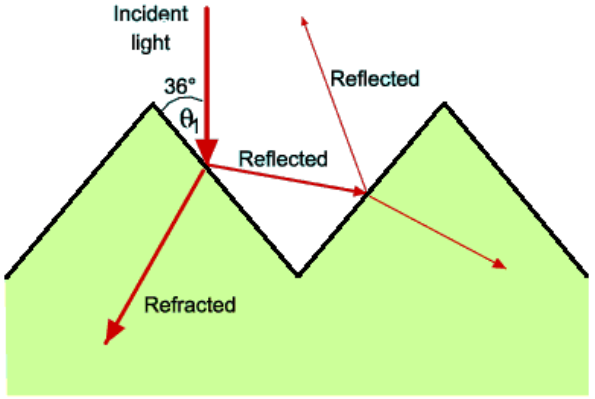
$$n_1 \sin \Theta_1 = n_2 \sin \Theta_2$$

$$\Theta_2 = \sin^{-1}\left(\frac{n_1}{n_2}\sin \Theta_1\right)$$

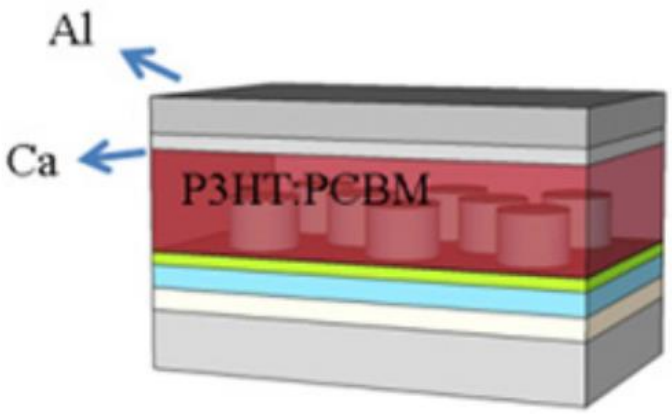




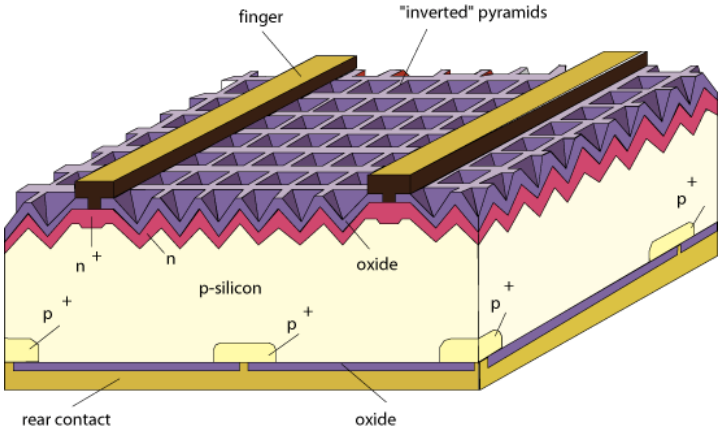
Internal Reflection



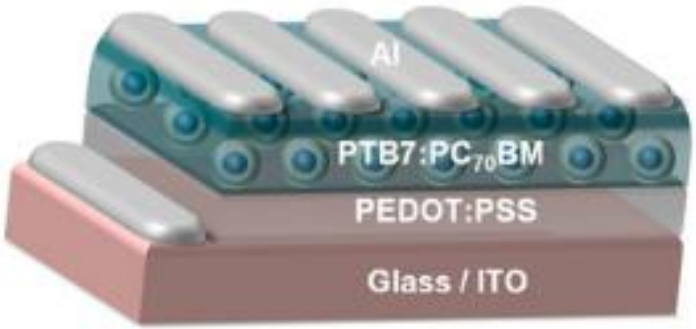
Light Trapping in Literature



Y. Liu, et al. J. Phys. D: Appl. Phys. **46** (2013) 24008

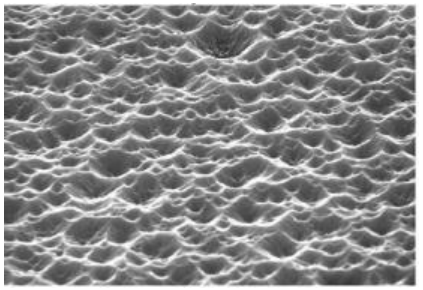


J. Zhao, et al. SOLMAT **42** (1996) 87



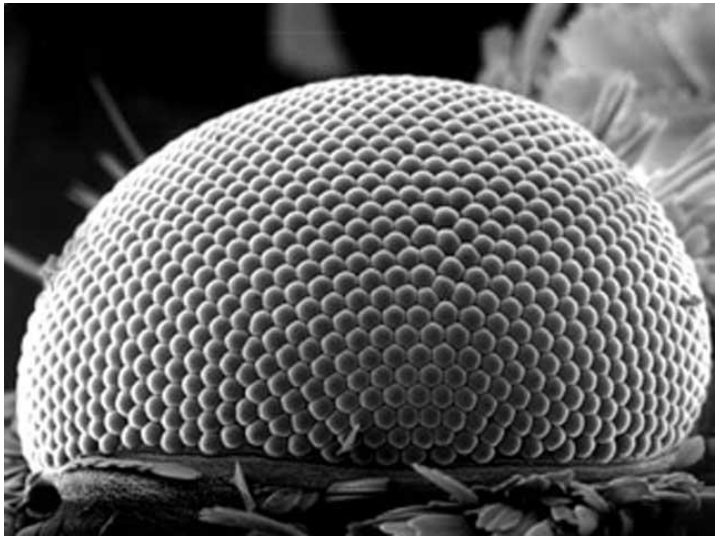
H. Choi, et al. Nano Lett. **13(5)** (2013) 2204

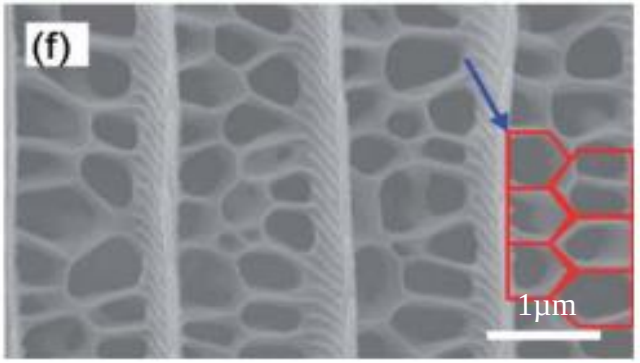
- Laser Texturing
- Chemical Etching
- Nanowires
- Nanoholes
- Surface Texturing



M. Berginski, et al. J. Appl. Phys. **101** (2007) 74903

Light Trapping in Nature



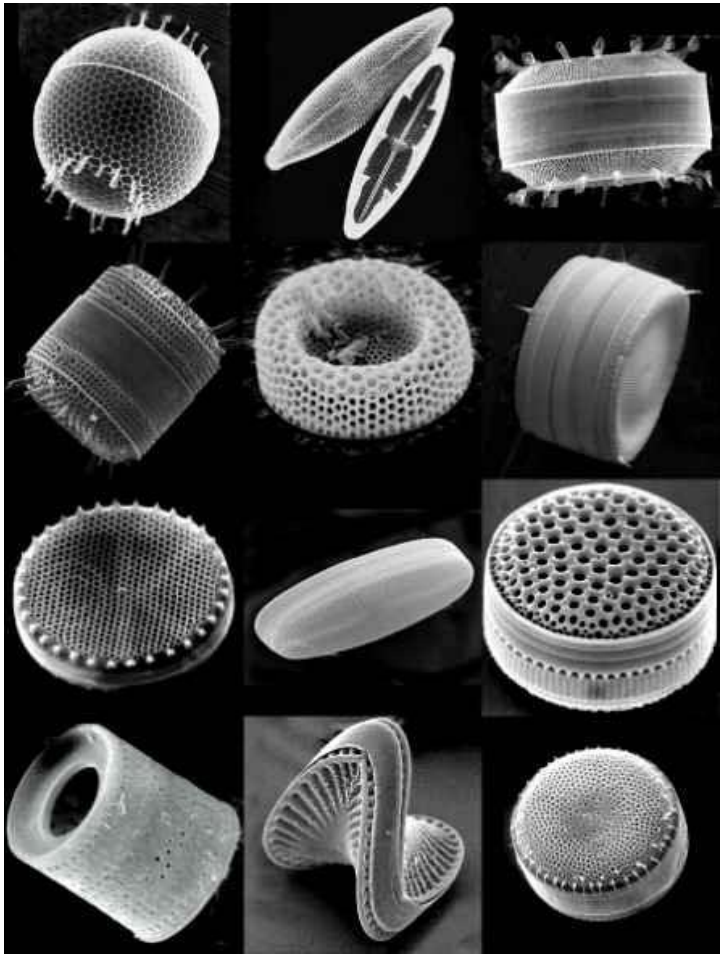


W.L. Min, et al. Adv. Mater, 2008, **20**, 3914
D.G. Stavenga, et al. P. Roy Soc B-Biol Sci, 2006, **273**, 661

Z. Han, et al. Nanoscale, 2012, **4**, 2879-2883
Z. Han, et al. Nanoscale, 2013, **5**, 8500-8506

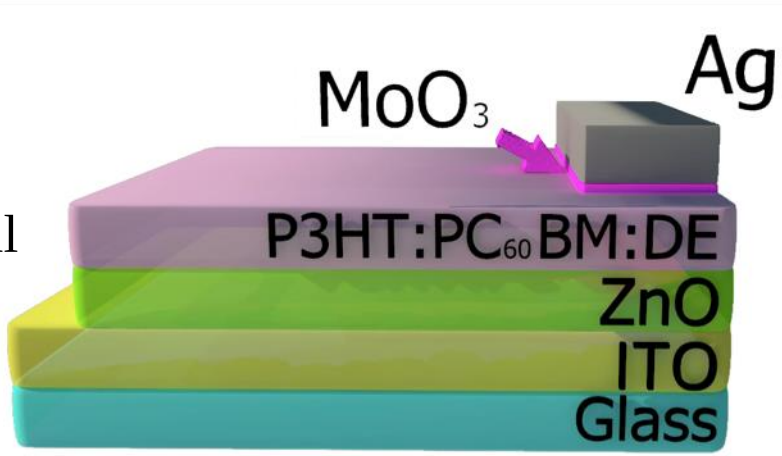
Biomimetic Light Trapping Approach

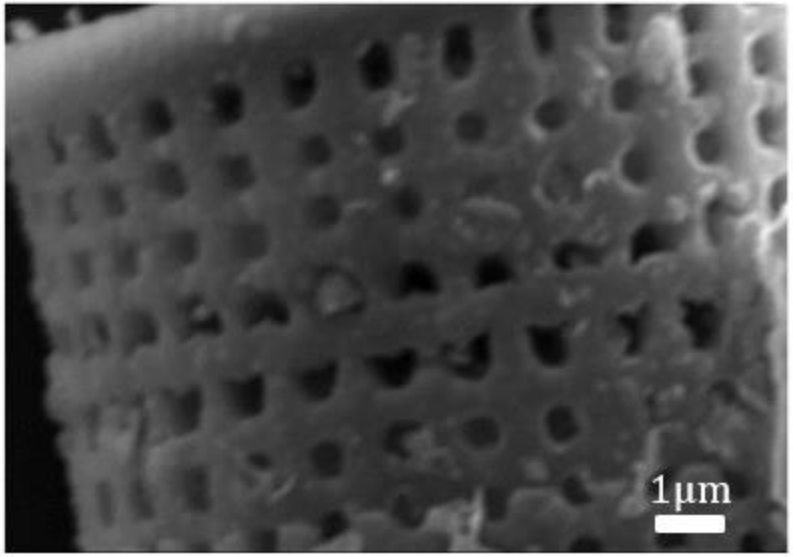
- Diatom Algae
- Earth Abundant
- 3D Nanostructured silica frustule
- Trap light for photosynthesis

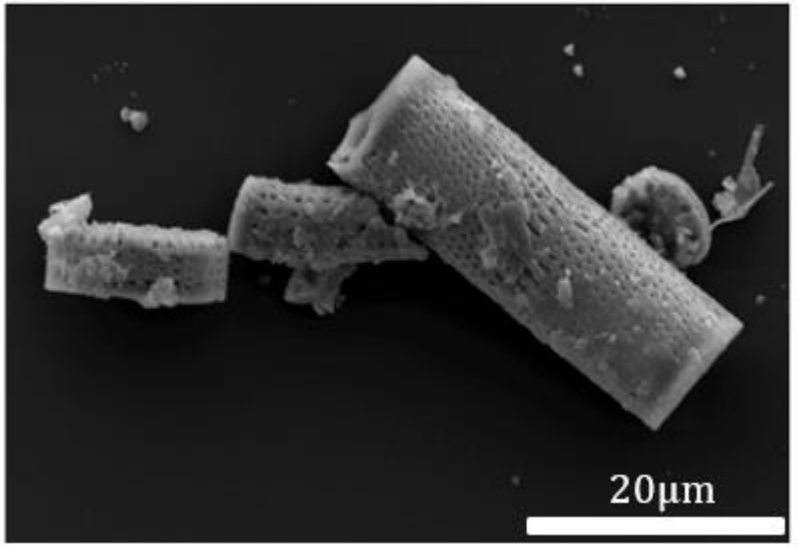


Diatomaceous Earth (DE)

- Fossilized remains of diatom algae
- Photonic Crystal (PhC)
- Absorption spectrum matches chlorophyll
- Average length ~ 20 um
- Active layer thickness ~200 nm







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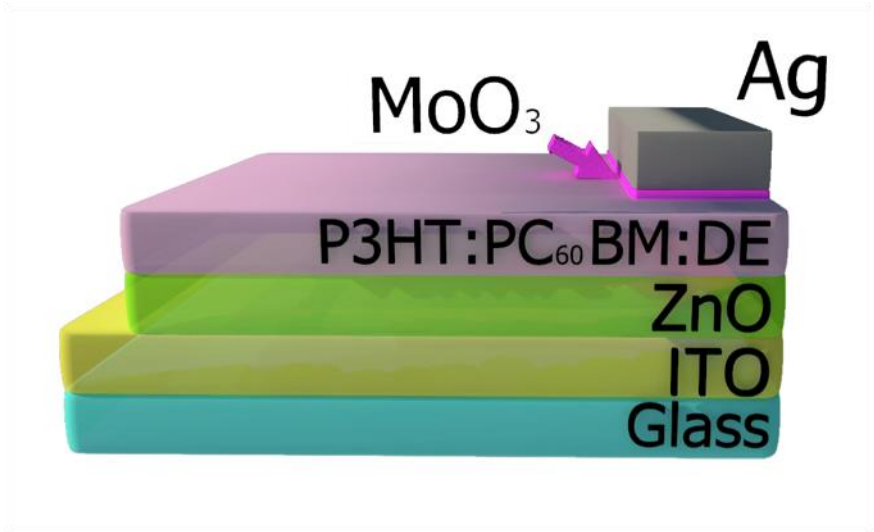
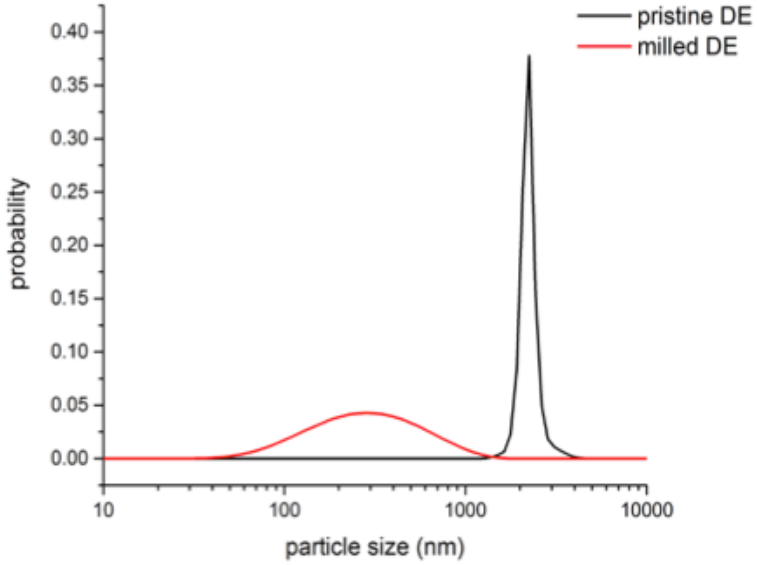
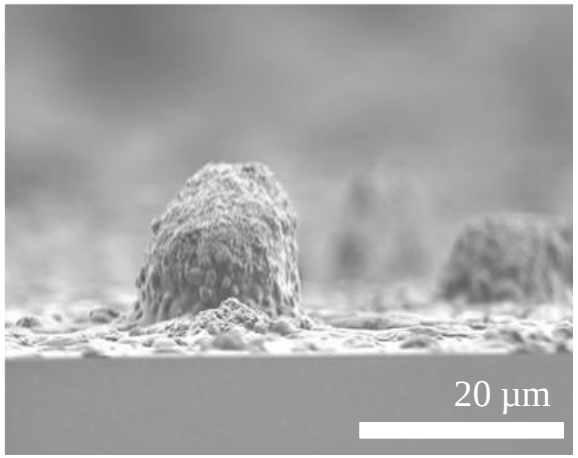
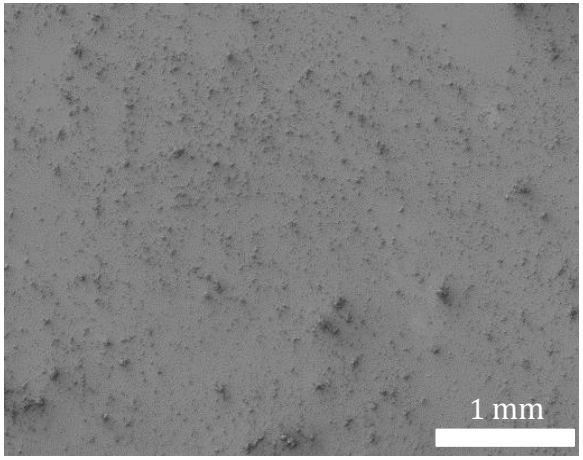
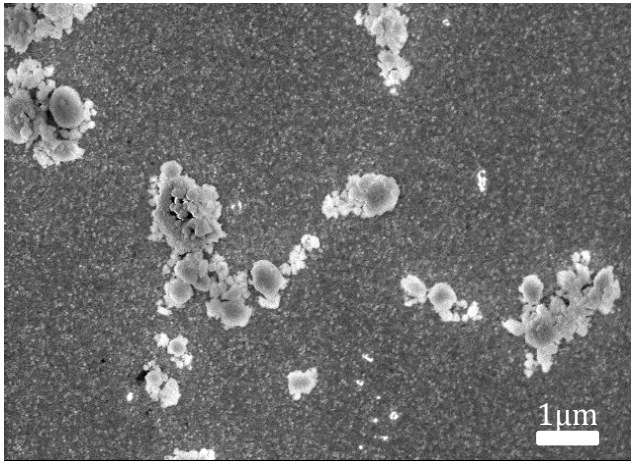
Device Fabrication











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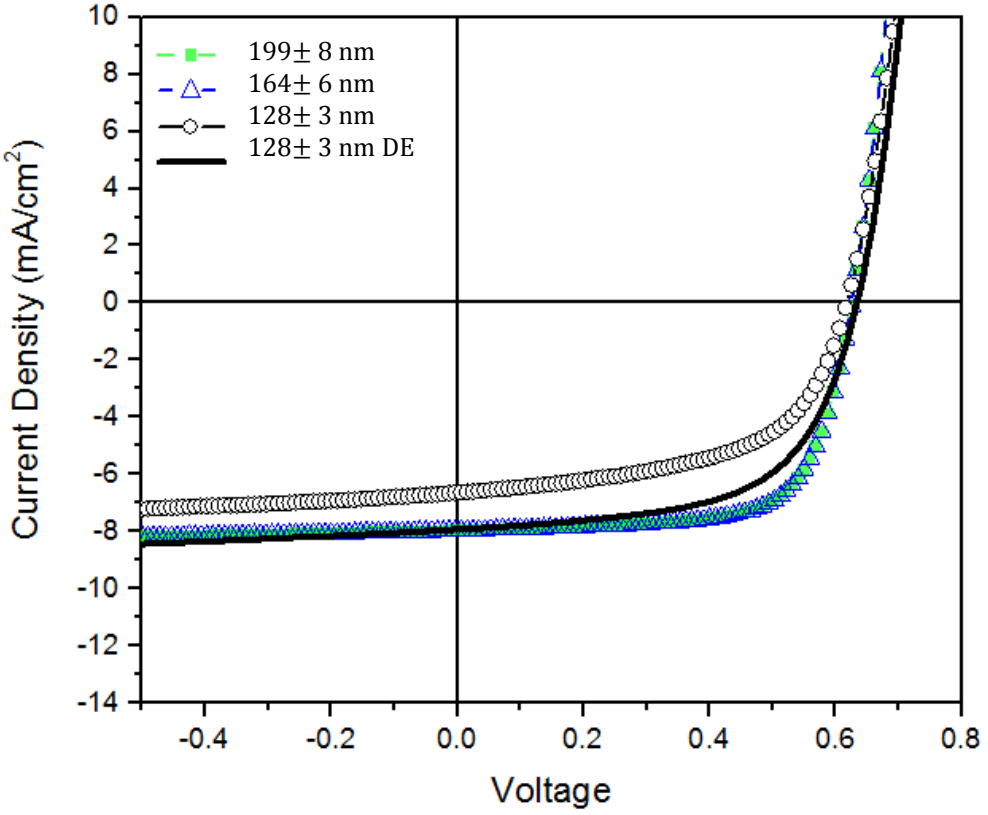
Optimal Cell Loading



Addition of DE allows a **36% thinner active layer to achieve comparable PCE** to device with standard active layer thickness.

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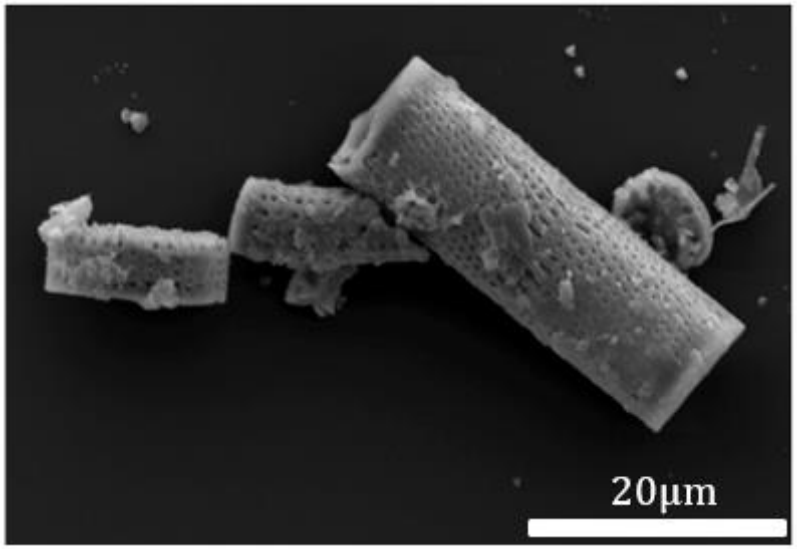
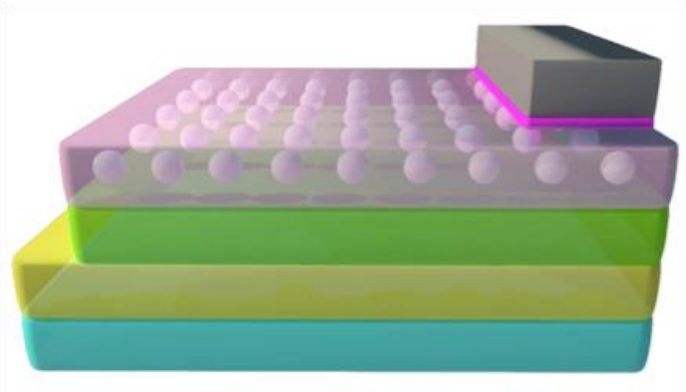
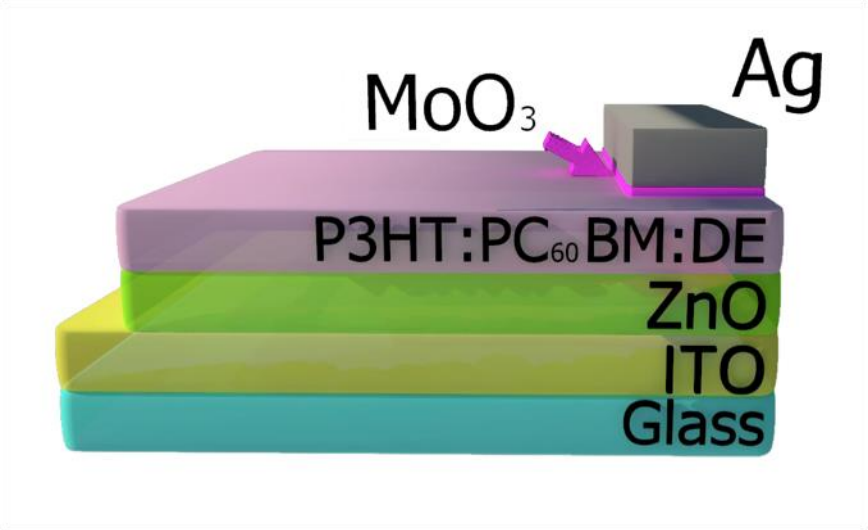
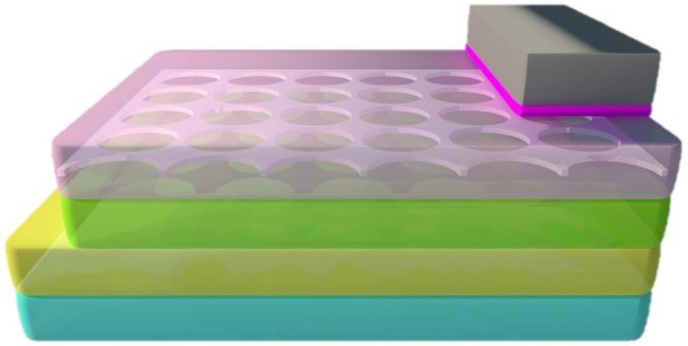
Pristine DE as Simulated Light Trap









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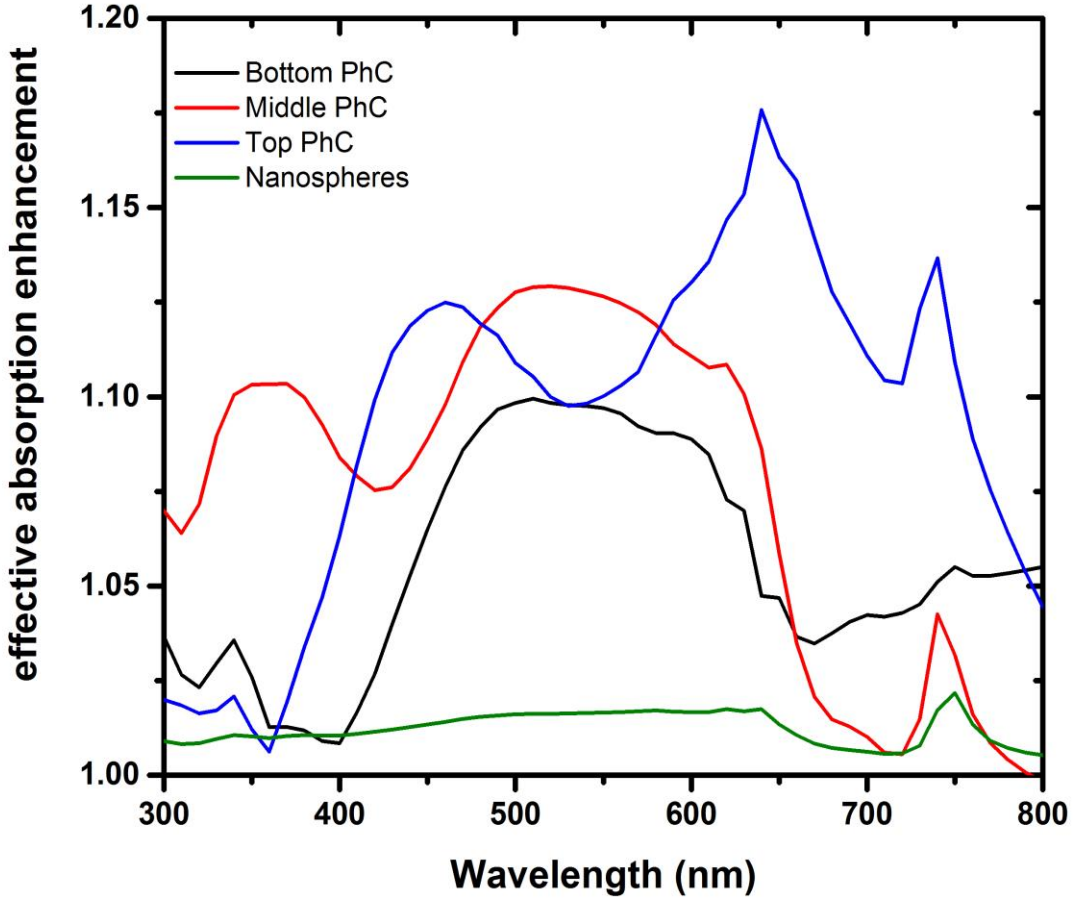
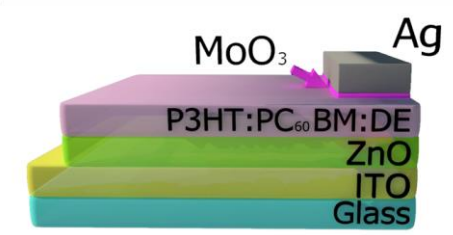
Simulation Results





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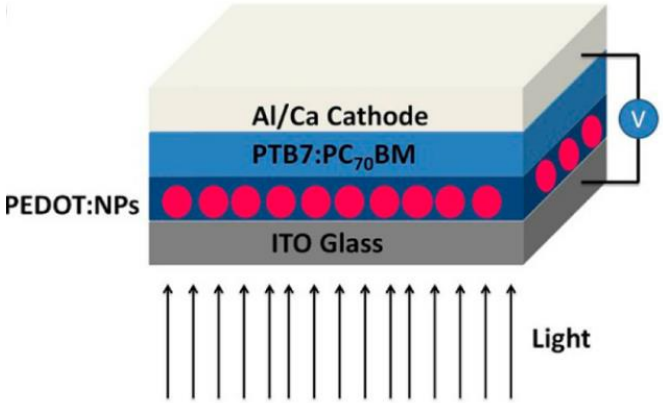
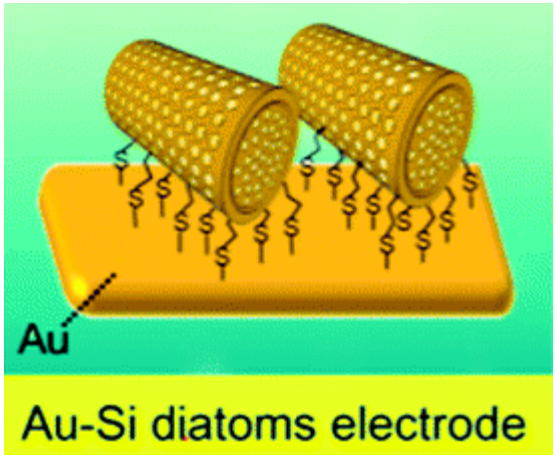
Further Applications of DE

- Plasmonic resonators
- Patterned electrodes
- Anti reflective coatings



L. Lu, et al. Nano Lett. **13(1)** (2013) 59



S. Chandrasekaran, et al. Chem Commun. **50** (2014) 10441

Design Rules for DE Inspired Solar

The frustule or PhC replica:

1. must be applied within active layer to ensure photon absorption results in exciton generation
2. can be implemented in any solution processable solar cell
3. should be positioned in imbedded orientation for optimal device performance

Future Work

- Conduct experiments to create design rules for various types of solar modules
- Produce and test optimal simulated device
- Couple DE inspired PhC with other solar phenomena (plasmonic resonance, FRET) to further enhance device performance

Q: What else can we learn from nature to develop more efficient electronics?

Image from: Chem. Rev. Soc. (2014), **43**, 588

Acknowledgements

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- Dr. Al Hepp
- Jeremiah McNatt

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- Yale University Rock Preparation Laboratory